

## Original Research Article

## Sizing of thermal energy storage devices for micro-cogeneration systems for the supply of domestic hot water



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## ABSTRACT

Cogeneration technologies are increasingly being utilised in the construction sector. Micro-cogeneration technologies only become economically feasible after they have been in operation over a lengthy period of time and this makes necessary the sizing of appropriate storage systems. The integration of cogeneration within overall heating and cooling loads requires the use of complicated simulation codes. However the need for this integration can be removed with the design of a cogeneration system which only covers the thermal demand required for the provision of domestic hot water, this demand being relatively easy to forecast. Based on a given domestic hot water demand, a calculation procedure for sizing the storage system is presented. This procedure is experimentally validated with only minor differences between expected and actual results, this being attributable to the limitations of the experimental set-up. It achieves more than acceptable results when compared with other model designed for heating applications in the building sector.

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## Introduction

Cogeneration, also known as combined heat and power (CHP), is a highly efficient method of utilising fossil resources and its use has therefore become increasingly widespread in the construction sector in the search for primary energy savings, reductions in electricity transport losses and security of supply [1,2]. Combined with renewable resources, it has also been demonstrated to be a rational way of cutting building CO<sub>2</sub> emissions [3]. From a technological point of view, cogeneration is available in a number of modalities: reciprocating internal combustion engines, micro-turbines, fuel cells, and reciprocating external combustion engines based on Stirling cycle [4,5].

The building sector differs from the industrial sector due to the variable profile of the demand. It is thus necessary to make an appropriate choice in terms of the size of engines and operating strategy [6–8]. In order to achieve the optimal operation of the system, an energy storage system is required [9]. There are a variety of options, including stratified hot water [8,10] phase change materials [11] and the use of the ground as a heat reservoir [3,12].

The variability of demand referred to above necessitates the use of computational codes in the design phase in order to analyze the coupling between the storage system, the demand and the engine [6,10,13–15]. It is even necessary to define procedures for creating demand profiles and selecting representative climate loads [16,17].

In the operation phase the performance of the system has to be monitored in order to correct deviations and achieve selected goals [10,18,19].

Experience in the modelling of the storage system, which involves the use of numerical methods to solve the dynamic of the problem, comes from the production of thermal solar energy [20,21]. With regard to cogeneration systems, the accurate modelling of the storage system has been demonstrated to be a key factor in the performance of the plant, in both technical [22] and economic terms [5,23].

This paper presents a special method of integrating cogeneration into a building, which is the supply of domestic hot water (DHW). The demand profile for domestic hot water, although an hourly variable, is easily forecasted, and is therefore possible to formulate an analytical procedure for the sizing of the thermal storage system. Avoiding sophisticated numerical procedures entails the deployment of cogeneration in the supply of domestic hot water, permitting an increased use of this technology in the building sector. Today, charts and diagrams exist for the sizing of suitable thermal storage systems [25], the importance of the accurate sizing of the thermal energy storage system for the profitability of micro-cogeneration systems for residential building applications having been demonstrated [5]. This paper presents a systematic calculation procedure which includes a simple equation for the integration of cogeneration in domestic hot water systems. This procedure has been validated in an experimental set-up which reproduces the demand in 100 flats and has been compared with other method proposed in the literature [25].

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## Nomenclature

### Greek symbols

|                 |                                     |
|-----------------|-------------------------------------|
| $\varepsilon_n$ | decision variable [–]               |
| $\rho_w$        | water density [kg/dm <sup>3</sup> ] |

### Latin symbols

|          |                                                                   |
|----------|-------------------------------------------------------------------|
| $BUE_n$  | back-up energy at $n$ period [kWh]                                |
| $C_d$    | DHW consumption volume in a day [dm <sup>3</sup> ]                |
| $C_{du}$ | DHW unitary consumption volume in a day [dm <sup>3</sup> /person] |
| $C_n$    | DHW consumption flow rate at $n$ -period [dm <sup>3</sup> /h]     |
| $C_w$    | water specific heat [kWh/kg K]                                    |
| CHP      | combined heat and power                                           |
| DHW      | domestic hot water                                                |
| $H_{bu}$ | thermal power supplied by the back-up system to the demand [kW]   |
| $H_c$    | thermal power to supply domestic hot water [kW]                   |
| $H_d$    | thermal power delivered by cogeneration system to demand [kW]     |
| $H_e$    | thermal power released by the engine at the heat exchanger [kW]   |

|            |                                                                                             |
|------------|---------------------------------------------------------------------------------------------|
| $N_f$      | number of flats [–]                                                                         |
| $N_p$      | number of persons per flat [–]                                                              |
| $Q_c$      | volume flow rate of domestic hot water [dm <sup>3</sup> /h]                                 |
| $Q_e$      | volume flow rate through the heat exchanger in the experimental set-up [dm <sup>3</sup> /h] |
| $SE$       | actual stored energy in the tank of the experimental set-up [kWh]                           |
| $SE_{max}$ | maximum amount of storable energy [kWh]                                                     |
| $SE_{n-1}$ | stored energy at $n - 1$ period [kWh]                                                       |
| $SE_n$     | stored energy at $n$ period [kWh]                                                           |
| $T_d$      | achieved DHW use temperature with the experimental system [°C]                              |
| $T_i$      | net water temperature [°C]                                                                  |
| $T_k$      | measured temperature at position $k$ in one tank [°C]                                       |
| $t_n$      | $n$ period long [h]                                                                         |
| $T_p$      | DHW supply temperature [°C]                                                                 |
| $T_u$      | DHW use temperature [°C]                                                                    |
| $V$        | volume of the storage device [dm <sup>3</sup> ]                                             |
| $WE_n$     | waste energy at $n$ period [kWh]                                                            |

## Methodology

### System description

The cogeneration system modelled in this paper is designed to be integrated within the DHW supply system of a centralized plant. The demand is therefore that of a certain number of flats (typically more than 80) whose DHW is supplied by a thermal plant. The cogeneration engine is designed to cover the minimum demand, that is, when the temperature of the net water is at its peak. A complementary thermal system is therefore necessary to support the cogeneration engine in covering the demand at other times. This system is sized for the continuous operation of the engine without any dissipation of waste energy. Consequently, thermal power from engine is given by Eq. (1).

$$H_e \cdot 24 = C_d \cdot \rho_w \cdot C_w \cdot (T_u - T_i) \quad (1)$$

Thermal storage is achieved with the stratification of hot water in the tank. Therefore when the overall volume of the tank is divided into various sub-tanks, each one is connected to the rest in a serial arrangement which achieves an appropriate variation of temperatures. The relation between the maximum amount of storable energy and the volume of the tank depends on the thermocline in the tank. Former regulations in Spain [24] recommend the relation given in Eq. (2). Assuming 60 °C for both the inlet ( $T_p$ ) and outlet ( $T_u$ ) temperatures of the storage system and a net water temperature ( $T_i$ ) of 16 °C, a conversion factor of 30.73 kWh/m<sup>3</sup> is obtained. Fig. 1 shows a general layout of the system.

$$SE_{max} = \rho_w \cdot C_w \cdot V \cdot (T_p - 0.4 \cdot T_u - 0.6 \cdot T_i) \quad (2)$$

### Sizing of the energy storage

Energy storage is necessary because DHW demand does not present a constant profile over time. Consequently the first step is to define a demand profile for DHW. In Spain the Technical Building Code [23] does not define this profile but only the water consumption per person per day. A continuous consumption has been assumed between 5 a.m. and 11 p.m., with three peaks

overlaid over this continuous consumption, one of 2 h at 7 a.m., and two of 1 h at 3 p.m. and 9 p.m. Fig. 2 shows the resulting profile. Other profiles are possible and numerical results will vary accordingly. However, the calculation procedure will still be valid.

The ratio of peak to minimum consumption depends on the number of users (flats): the higher the number of users, the lower this ratio. Again, Spanish regulations do not impose any ratio, so a reasonable relation has been assumed (Fig. 3), based again on former Spanish regulations [24]. For a given number of flats, Fig. 3 determines the peak to minimum consumption ratio and by integrating the profile given in Fig. 2 we can calculate the consumption (flow rate) for peak and minimum demand periods, when consumption in a day is assumed to be 22 L at 60 °C per person in a three-person per flat [23].

The calculation procedure for the system includes two phases: the sizing of the storage device and the calculation of the possible amount of waste energy and energy supplied by the back-up system (back-up energy).

The sizing phase begins with the calculation of the thermal power taken from the engine, which has to be able to cover the energy demand required to supply the consumption of DHW in a day. In order to avoid the dissipation of thermal energy from the engine, this calculation is made for maximum net water temperature, this information normally being available for periods of one month. Consequently, except for during the design month, the back-up system is always supplying an amount of energy to complete the thermal demand resulting from the supply of DHW.

Sizing calculation is an iterative procedure and an initial size ( $SE_{max}$ ) is therefore assumed. The procedure begins with the application of the energy balance given in Eq. (3) to each period (peak, minimum demand or zero consumption). The application of Eq. (3) produces a value of  $\varepsilon_n$  which, according to Table 1, determines the quantity of waste energy, back-up energy and stored energy at the end of the  $n$ -period, all of which will be used in the balance in the next period.

$$SE_{n-1} + H_e \cdot t_n = C_n \cdot t_n \cdot \rho_w \cdot C_w \cdot (T_u - T_i) + \varepsilon_n \cdot SE_{max} \quad (3)$$

Once Eq. (3) has been applied to a complete day, the overall quantity of waste energy and back-up energy can be calculated. The

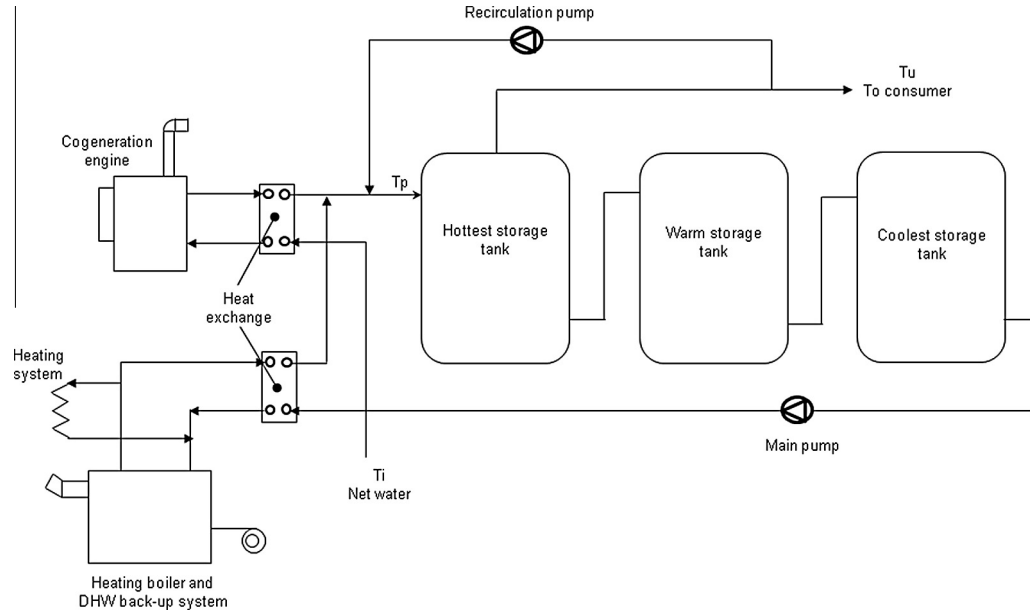


Fig. 1. General layout.

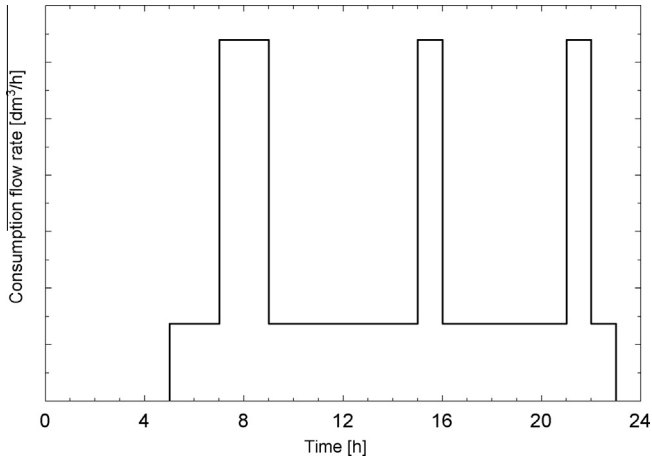


Fig. 2. DHW demand profile.

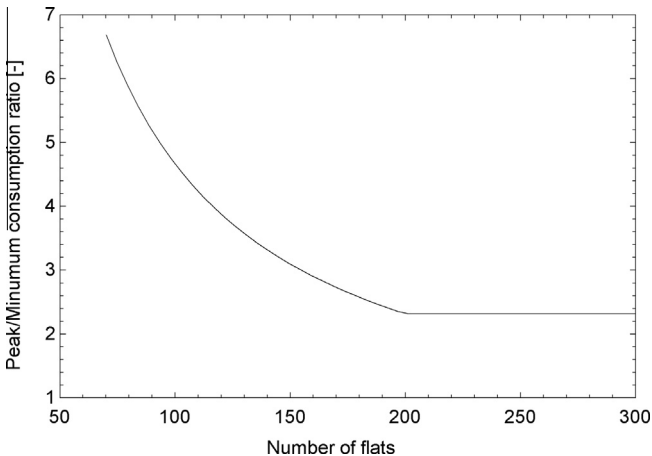


Fig. 3. Effect of number of flats on peak to minimum consumption ratio.

Table 1

Waste energy, back-up energy and stored energy at n-period depending on variable  $\varepsilon_n$  given in Eq. (3).

|                         | $WE_n$                                | $BUE_n$          | $SE_n$                          |
|-------------------------|---------------------------------------|------------------|---------------------------------|
| $\varepsilon_n < 0$     | 0                                     | $-\varepsilon_n$ | 0                               |
| $0 < \varepsilon_n < 1$ | 0                                     | 0                | $\varepsilon_n \cdot SE_{\max}$ |
| $1 < \varepsilon_n$     | $(\varepsilon_n - 1) \cdot SE_{\max}$ | 0                | $SE_{\max}$                     |

optimum size for the storage device is the minimum one capable of producing zero waste energy and zero back-up energy.

The second phase of the calculation procedure consists in applying month by month the energy balance given in Eq. (3). We thus obtain figures for the percentage of demand covered and of back-up energy obtained for each water supply temperature. Due to the design procedure, no waste energy is released in any month. Back-up energy is required in order to cover the demand except in the design month.

By combining Eqs. (1) and (3), a relation between stored energy at period n-1 and the maximum stored energy is obtained (Eq. (4)). Taking into account Eq. (2), it is concluded that the volume of the storage tank is independent from water supply temperature for a given use temperature.

$$SE_{n-1} - \varepsilon_n \cdot SE_{\max} = \left( C_n - \frac{C_d}{24} \right) \cdot t_n \cdot \rho_w \cdot C_w \cdot (T_u - T_i) \quad (4)$$

#### Experimental set-up

An experimental set-up was built to verify the model. A Sener-tec engine model DACHS HKA-G of 5.5 kW<sub>e</sub> and 10.8 kW<sub>th</sub> was coupled with three 750 L tanks, which are shown in Fig. 1, except for the supplementary system, which has been removed. The flow rate consumed by 100 flats with the profile shown in Fig. 2 was implemented with programmed electro-valves. With flow meters and temperature sensors, the thermal power recovered from the engine and supplied to meet demand was measured. To calculate the quantity of stored energy, nine thermocouples were used to determine the thermocline in the three tanks. Fig. 4 shows the layout of the experimental set-up, with the names of the main

variables. Water supply temperature was 16.8 °C and 3 persons were assumed to be living in each flat, with a daily DWH consumption of 22 L at 60 °C.

The demand power ( $H_c$ ), engine thermal power ( $H_e$ ), power delivered by the system ( $H_d$ ) and back-up power ( $H_{bu}$ ) are given by Eqs. (5)–(8). The stored energy in the overall storage volume is calculated by Eq. (9).

$$H_c = Q_c \cdot \rho_w \cdot C_w \cdot (T_u - T_i) \quad (5)$$

$$H_e = Q_e \cdot \rho_w \cdot C_w \cdot (T_{oe} - T_{ie}) \quad (6)$$

$$H_d = Q_c \cdot \rho_w \cdot C_w \cdot (T_d - T_i) \quad (7)$$

$$H_{bu} = Q_c \cdot \rho_w \cdot C_w \cdot (T_u - T_d) = H_c - H_d \quad (8)$$

$$SE = \frac{V}{9} \cdot \sum_{k=1}^9 \rho_w(T_k) \cdot C_w \cdot (T_k - T_i) \quad (9)$$

Experimental results were stored in a data logger and then processed in order to analyse the evolution of power and energy fluxes. Back-up energy was calculated as the difference between the energy demand and the energy supplied by the cogeneration system (Eq. (8)).

## Results

### Sizing results

The application of Eq. (4) to the consumption profile given in Fig. 2 and to the peak to minimum demand ratio given in Fig. 3 produces a set of data given in Fig. 5. These can be fitted by Eq. (10), with a correlation coefficient of 99.9%.

$$V = (8.179 + 0.3843 \cdot N_f) \cdot (C_{du} \cdot N_p) \quad (10)$$

Eq. (10) gives the minimum volume of the storage tank for a number of flats. This volume also determines the maximum engine thermal power from Eq. (1). If the actual volume is lower than the one given for Eq. (10) the size (thermal power) of the engine has to be reduced to avoid the dissipation of energy or to increase the demand. In the latter case, the engine will not cover the entire demand but there will no energy dissipation.

The application of Eq. (1) to the engine in the experimental set-up gives us 78 flats. Eq. (10) therefore requires a minimum storage

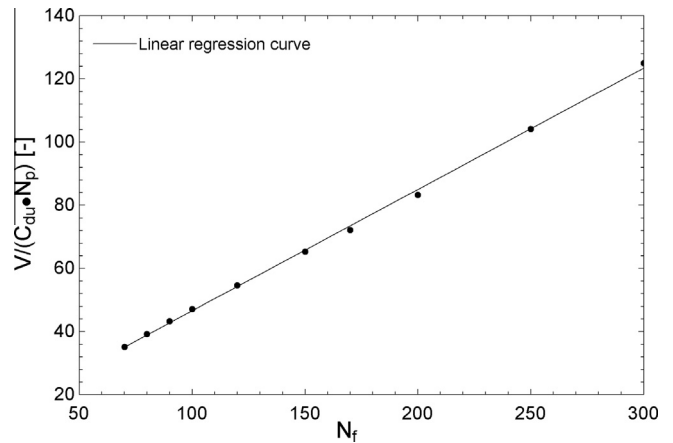


Fig. 5. Curve fitting for thermal storage volume.

volume of 2518 L to cover 100% of the demand with the given engine. Bianchi et al. [25] present some charts to be used in the assessment of the minimal size of the thermal storage system in a residential micro-CHP application. Although they are designed for heating demand rather than for the demand for domestic hot water, the assumed profile is relatively similar to that given in Fig. 2, and so the results of both procedures can be compared. For 78 flats and the engine used in the study, the peak of thermal power is 40.92 kW, which, using the model given in [2], requires a storage volume of 73.67 kWh. Taking into account the energy density given by the prescribed temperatures (30.73 kWh/m<sup>3</sup>) a storage volume of 2397 L is obtained, very similar to that given by Eq. (10), which does not require the use of any charts.

### Experimental results

Substituting the actual storage volume of the experimental set-up (2250 L) in Eq. (10) (storage volume) 68 flats are obtained, against 78 derived from Eq. (1) (engine). Thus the available storage is less than that which is required for the engine. This means that the thermal energy equivalent to 10 flats would have to be released. Another possibility would be to increase the demand at least in those 10 flats, setting a demand of 88 flats. In order to

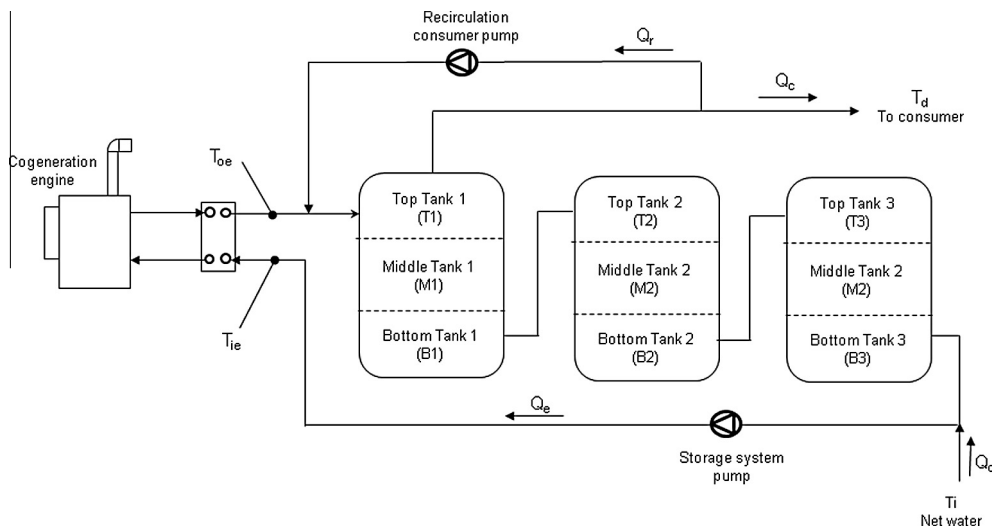


Fig. 4. Experimental layout with the names of the main variables.

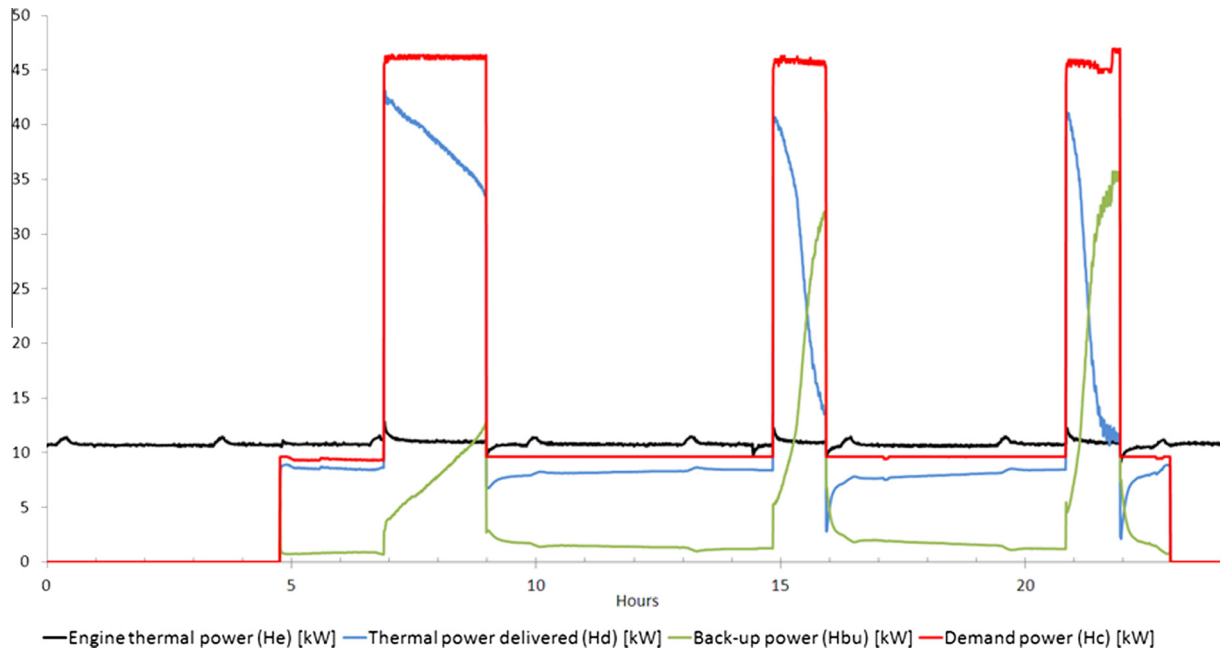


Fig. 6. Experimental results (power balance).

ensure the release of no thermal energy, there are assumed to be 100 flats.

Fig. 6 shows the experimental results with respect to the evolution of power over time. In Fig. 7, the measured stored energy (Eq. (9)) in the overall volume is overlaid onto the demand power and the thermal power delivered by the system. It can be observed that the amount of thermal power from the engine is higher than the minimum demand, with the result that the storage of energy (charge of energy in tank) occurs in both minimum demand and no consumption periods. During peak demand periods the discharge of the thermal energy stored in the tank takes place.

From 11.00 p.m. to 5.00 a.m., without any demand, the largest quantity of energy is stored. From 5.00 a.m. to 7.00 a.m. (points A–B in Fig. 7) the minimum demand reduces the rate of storage and from 7.00 a.m. to 9.00 a.m. (B–C) the first discharge of the tank

takes place. Due to the fact that engine output temperature (an average of 56 °C) is lower than the water use temperature, a limited back-up power is needed during minimum demand periods, and this increases in peak periods. At the end of the first peak period, point C, there is approximately 7 kWh remaining in the tank. That is, the back-up system is delivering energy although there is stored energy left. This behaviour is also observed throughout the entire peak period, with a requirement for an increasing amount of back-up power in response to a reduction in the quantity of stored energy in the tank.

The explanation for the fact that energy is supplied from the back-up system when there is stored energy left is the rate of discharge of that energy. Fig. 8 explains the charge and discharge processes. When there is no demand (from 11.00 p.m. to 5.00 a.m.), the greatest amount of energy is stored. In this period, the water

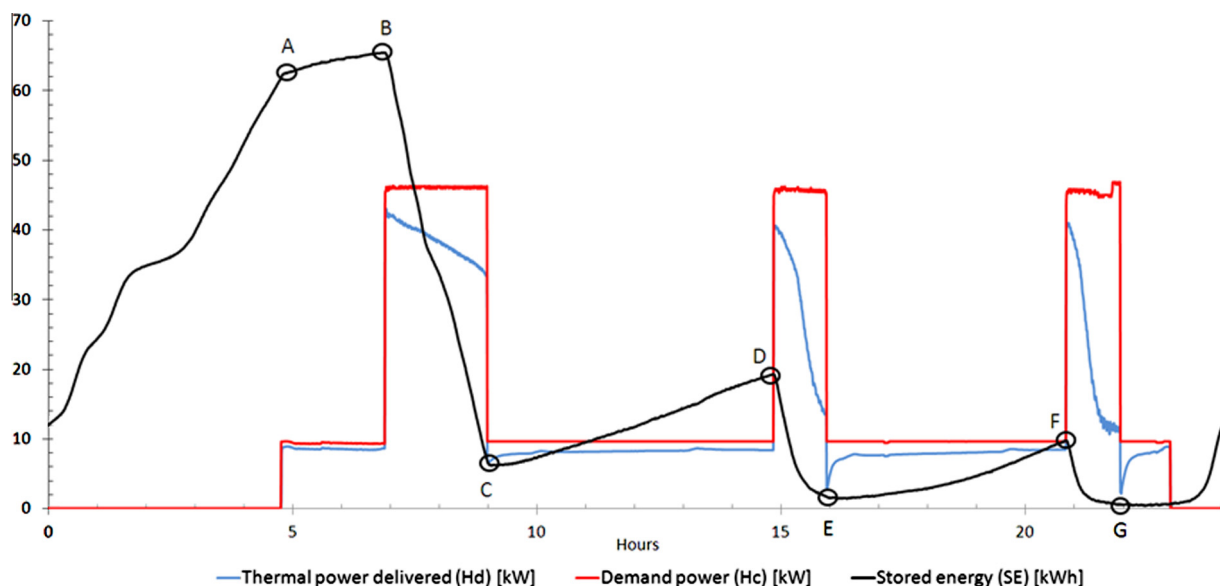


Fig. 7. Experimental results (stored energy overlaid on power balance).



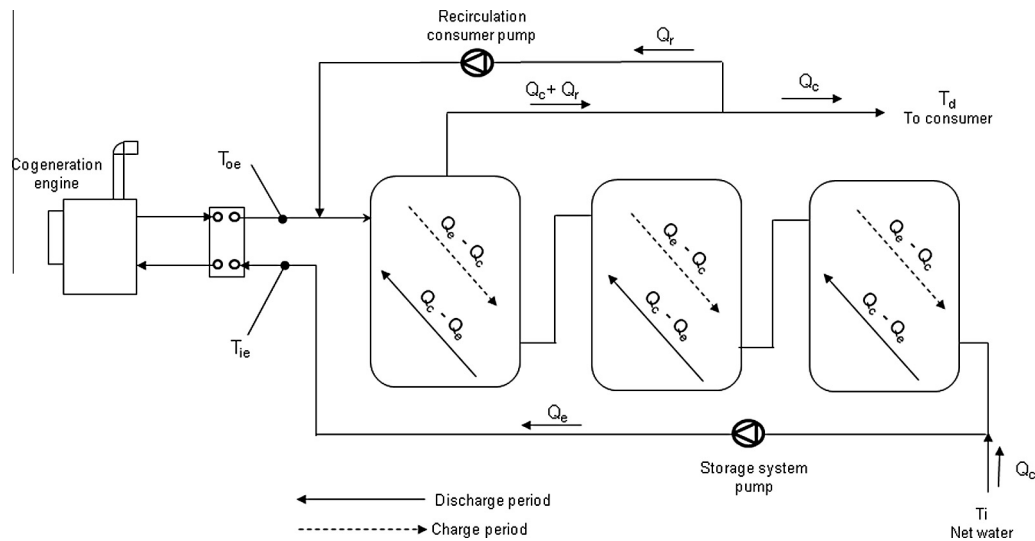


Fig. 8. Charge and discharge process.

**Table 2**  
Distribution of stored energy [kWh] during peak demand periods.

|      | B     | C    | D     | E    | F    | G    |
|------|-------|------|-------|------|------|------|
| T1   | 11.49 | 4.19 | 10.85 | 0.78 | 7.91 | 0.17 |
| M1   | 11.49 | 1.65 | 5.91  | 0.35 | 1.27 | 0.09 |
| B1   | 11.49 | 0.70 | 1.77  | 0.26 | 0.29 | 0.09 |
| T2   | 11.10 | 0.12 | 0.43  | 0.03 | 0.09 | 0.00 |
| M2   | 10.54 | 0.09 | 0.12  | 0.09 | 0.03 | 0.03 |
| B2   | 8.42  | 0.09 | 0.09  | 0.09 | 0.06 | 0.06 |
| T3   | 0.67  | 0.06 | 0.06  | 0.06 | 0.03 | 0.03 |
| M3   | 0.20  | 0.09 | 0.06  | 0.03 | 0.06 | 0.06 |
| B3   | 0.06  | 0.03 | 0.00  | 0.03 | 0.00 | 0.03 |
| Tank | 65.5  | 7.0  | 19.3  | 1.7  | 9.7  | 0.6  |

**Table 3**  
Average flow rates and duration of peak demand periods.

|                                  | BC    | DE    | FG    |
|----------------------------------|-------|-------|-------|
| $Q_e$ [dm <sup>3</sup> /h]       | 298.5 | 296.4 | 285.7 |
| $Q_c$ [dm <sup>3</sup> /h]       | 920.8 | 913.0 | 909.3 |
| $Q_c - Q_e$ [dm <sup>3</sup> /h] | 622.3 | 616.6 | 623.7 |
| Duration [h]                     | 2.085 | 1.08  | 1.105 |

from the bottom of the coolest tank (B3) is sent to the heat exchanger and then sent to the top of the hottest tank (T1). In a minimum demand period, the flow rate taken from the water supply is lower than that through the heat exchanger, so the thermal power released by the engine is delivered to both the tank and the demand (Fig. 7 shows how energy is stored in AB, CD and EF, with approximately the same slope). Finally, in a peak demand period, the demand flow rate is higher than the heat exchanger rate so energy supplied to the demand is taken from both the heat exchanger and the tank.

Table 2 shows how the stored energy is distributed between the three tanks in peak demand periods. Table 3 gives the flow rates and duration of these periods. It is possible to explain the stored energy removal process by the pushing effect of the water in the tank from the bottom of the coolest one (B3) to the top of the hottest one (T1). The displaced volume can be evaluated from the flow rate and the duration of the period. This volume, normalized by 750/3 L, is 5.19 for BC, 2.67 for DE and 2.76 for FG periods. Measuring these fractions from T1 in Table 2 57.71 kWh, 17.94 kWh and

9.40 kWh are obtained respectively. Removing these quantities from the stored energy at the beginning of each period produces 7.79 kWh, 1.36 kWh and 0.30 kWh, which are similar values to the amount of stored energy left in the tank at the end of each period (the last row of Table 2). Consequently the flow rate used to remove the stored energy is responsible for the remaining stored energy at the end of each peak demand period. This remaining stored energy, not considered in Eq. (3), will produce extra back-up energy.

It can be observed that the flow rate through the heat exchanger changes between minimum and peak demand periods. So in AB, 231.5 dm<sup>3</sup>/h are measured, increasing to 298.5 dm<sup>3</sup>/h in BC. This increase in the flow rate through the heat exchanger produces a lower flow rate through the tanks, reducing the discharge capacity. This notable fluctuation in flow rate is due to the absence of a consumption grid. Consequently, in the experimental set-up, the hot water produced is drained to atmospheric pressure, which adversely affects the flow rate distribution. This fact would not take place in a real set-up system.

From the experimental results, the actual back-up energy is 81.6 kWh, with 71.7 kWh being obtained if Eq. (4) is applied to the nominal values of the experimental case. The difference (9.9 kWh) is according to the total amount of remaining stored energy at the end of each peak demand period (9.3 kWh). This is due to the restriction imposed on the discharge process by the flow rates, a restriction which would possibly not be present in a real installation.

## Conclusions

The employment of micro-engines in cogeneration for the supply of domestic hot water requires the use of storage energy devices. This paper presents an analytical procedure for the estimation of the volume of these storage devices when they use the principle of stratified hot water, giving a simple equation for a typical consumption profile. The model was successfully compared with others designed to provide heating in the residential sector. An experimental set-up was also built to verify the proposed model. The results given by the model were similar in both experimental and theoretical scenarios, there being only slight differences in the experimental case, which can be explained by the limitations of the set-up in terms of its capacity to model a real installation.

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